Coronal and Stellar Mass Ejections
Proceedings IAU Symposium No. 226, 2005
K. P. Dere, J. Wang & Y. Yan, eds.

DOI: 10.1017/S1743921305000876

CME Interaction and the Intensity of Solar Energetic Particle Events

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Abstract.
Large Solar Energetic Particles (SEPs) are closely associated with coronal mass ejections (CMEs). The significant correlation observed between SEP intensity and CME speed has been considered as the evidence for such a close connection. The recent finding that SEP events with preceding wide CMEs are likely to have higher intensities compared to those without was attributed to the interaction of the CME-driven shocks with the preceding CMEs or with their aftermath. It is also possible that the intensity of SEPs may also be affected by the properties of the solar source region. In this study, we found that the active region area has no relation with the SEP intensity and CME speed, thus supporting the importance of CME interaction. However, there is a significant correlation between flare size and the active region area, which probably reflects the spatial scale of the flare phenomenon as compared to that of the CME-driven shock.

Keywords. shock waves, Sun: coronal mass ejections (CMEs), Sun: flares, Sun: X-rays, gamma rays, Sun: particle emission, solar-terrestrial relations

1. Introduction

Solar energetic particle (SEP) events with high intensity ($\geqslant$10 pfu in the > 10 MeV channel as measured by GOES) and duration exceeding a few hours are closely associated with coronal mass ejections (CMEs). This association was first pointed out by Kahler, Hildner, van Hollebeke, *et al.* (1978), leading to the idea that SEPs are accelerated by CME-driven shocks (Reames (1999)). One of the strongest evidences for shock acceleration is the observation of energetic storm particle (ESP) events (see e.g. Rao, McCracken, Bukata, (1967). ESPs are particles accelerated locally at the shock front and detected when the shock blows past the observing spacecraft. In the case of SEPs, the particles arrive at 1 AU in an hour or so, while the shock takes much longer ($\geqslant$ half a day). However, the CME that drives the shock can be detected when it is still near the Sun. The speed of the CMEs correlates reasonably well with the intensity of the associated SEP events (Kahler, Sheeley, Howard, *et al.* (1984), Kahler (2001), Gopalswamy, Yashiro, Lara, *et al.* (2003)), as one would expect if the particles are accelerated by the CME-driven shocks. Kahler, Sheeley, Howard, *et al.* (1984) showed that the SEP intensity is also well correlated with the apparent width of CMEs, suggesting that the kinetic energy of CMEs is an important factor deciding the intensity of SEP events. Since there is a reasonable correlation between CME speed and angular width, we consider just the correlation between SEP intensity and CME speed. One of the major problems with this correlation has been that the scatter is very large: for a given CME speed the SEP intensity can vary over 3 orders of magnitude. Finding an explanation for this large scatter is an important part of understanding the origin of SEPs. This is a complex problem because the particle acceleration depends on both the source (shock strength, free energy in the active region) and medium (presence of seed particles, presence of turbulence in the ambient medium, orientation of the ambient magnetic field with respect to shock normal, connectivity of the acceleration region to the observing spacecraft) properties. Kahler (2001) pointed out the presence of seed particles in the ambient medium and the spectral variation between SEP events can account for one to two orders of magnitude scatter in the CME speed vs. SEP intensity plots.

Recently, Gopalswamy, Yashiro, Krucker, *et al.* (2004) found that the presence of preceding CMEs may also affect the intensity of SEP events: while the CME properties such as speed, width, mass, kinetic energy and source longitude were similar, SEP events with preceding CMEs had higher intensity. Another possibility is to attribute the SEP intensity variation to the properties of the active region. For example, the high intensity events may be from active regions that have large free energy and hence erupt more frequently. When eruptions happen frequently, one expects CME interaction. In order to see this connection, we examine how the active region properties affect the SEP intensity.

2. Data and Analysis

The data set used for this study is the same as that of Gopalswamy, Yashiro, Krucker, *et al.* (2004) consisting of all the distinct large (intensity of protons $\geqslant 10$ pfu in the > 10 MeV channel) SEP events from 1997-2002 that had overlapping observations from the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraphs (LASCO). There were 57 such events. Some of these events were backsided, so we do not know their flare and source properties. We also excluded events that did not originate from active regions. We consider the remaining 41 events for this study. For each one of these events, the primary CME, the associated flare, and the associated active region are known. We use all the information compiled in Table 1 of Gopalswamy, Yashiro, Krucker, *et al.* (2004). In addition, we compiled the area of the associated active regions, which we analyze in this paper. We examine how the SEP intensity is affected by the active region area.

Following Gopalswamy, Yashiro, Krucker, *et al.* (2004), we divide the SEP events into three groups: those with preceding CMEs (P events), (ii) those with no preceding CMEs (NP events), and (iii) those with other types of interaction (O events). The preceding CMEs were required to be wide (width $\geqslant 60°$) and originate within a day from the same active region as the primary CME. In O events the primary CMEs either interacted with a streamer or with a preceding CME before it emerged above the occulting disk of the coronagraph. The P events were the largest in number (19), with roughly equal number of NP (10) and O (12) events. Figure 1 shows a P event that occurred on 2000 November 24 along with other eruptions from the same region (AR 9236). Flares and CMEs erupted in quick succession from this region over a three-day period and the SEP intensity remained high for several days (see the distributions of flare and CME recurrence times in Figure 1). The SEP event was associated with a fast halo CME (1245 km/s) from AR 9236 located at N22W07 at the time (15:30 UT) of the eruption. About 10 h earlier, another fast (994 km/s) halo CME had erupted from the same region. Clearly, what was ahead of the 15:30 UT CME was not the normal solar wind, but the aftermath of the preceding CME. We suggest that if a shock acceleration mechanism is at work, then what enters into the shock is not the normal solar wind but the disturbed plasma behind the first CME or the first CME itself.

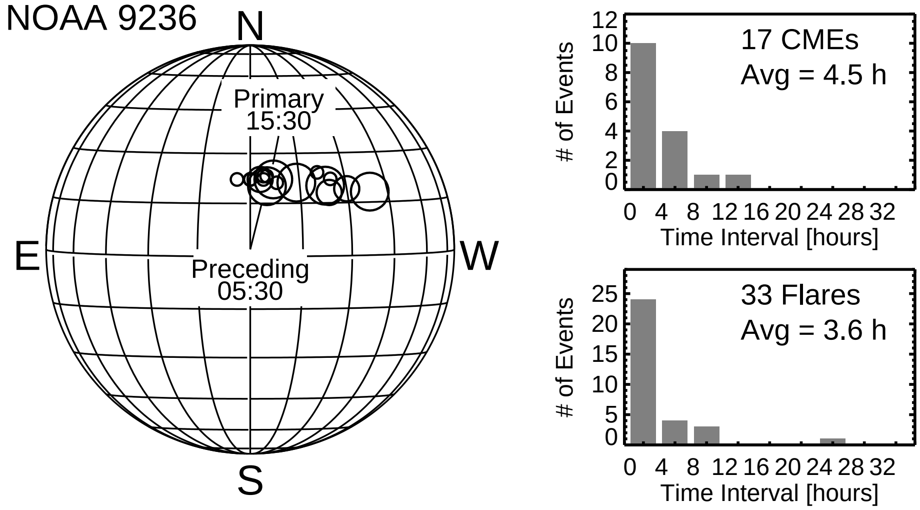

Figure 1. (left) Location of AR 9236 at the times of CME-associated flares during the period 2000 November 22-27, including one of the primary CMEs on November 24 (15:30 UT) with the preceding CME at 05:30 UT. The small, medium and large circles represent C, M, and X class flares, respectively. All the M and X class flares were associated with CMEs. (right) Histograms of CME and flare recurrence times from AR 9236. There were 33 soft x-ray flares (C, M, and X class) and 17 CMEs. The average flare and CME recurrence times are 3.6 h and 4.5 h, respectively.

2.1. *SEP Intensity and Active Region Area*

Figure 2(a-d) shows the distribution of the SEP intensities for all the events and for the three subgroups (P, NP, and O). We see that the P events have generally larger intensity compared to the NP events and the O events are have intermediate behavior. The P events are three times more likely to have higher intensity than the NP events, probably because of the presence of preceding CMEs that boost the acceleration efficiency of the primary shock via shock strengthening (Gopalswamy, Yashiro, Kaiser, *et al.* (2001)), and/or the presence of seed particles from the preceding eruption. Is it possible that the higher intensity has its origin in the active region itself? To check this, we have shown the distribution of active region area for all the SEP events as well as for the P, NP, and O events in Figure 2(e-f). The median value of the active region area is the largest for P events (880 millionths) and the smallest for NP events (500 millionths) and the O events had an intermediate value (620 millionths). The active regions of NP events have a slightly smaller area on the average. Does this mean higher intensity results from larger active regions?

The scatter plot between the SEP intensity and active region area in Figure 3(a) shows that there is little correlation between the two quantities (correlation coefficient r= 0.21). When we consider the individual subgroups, the correlation coefficient is worse for P (r= −0.02) and O (r= 0.04) events, while it seems better for the NP events (r= 0.46). It must be pointed out that there were only 10 NP events and the correlation is almost lost (r= 0.26) if we exclude the single outlier NP event. For a given active region area, the intensities of P and O events vary over three orders of magnitude. There is considerable overlap between NP and O events on the plot, but the P events clearly have higher intensity. Thus the area of the active region does not seem to significantly order the SEP intensity.

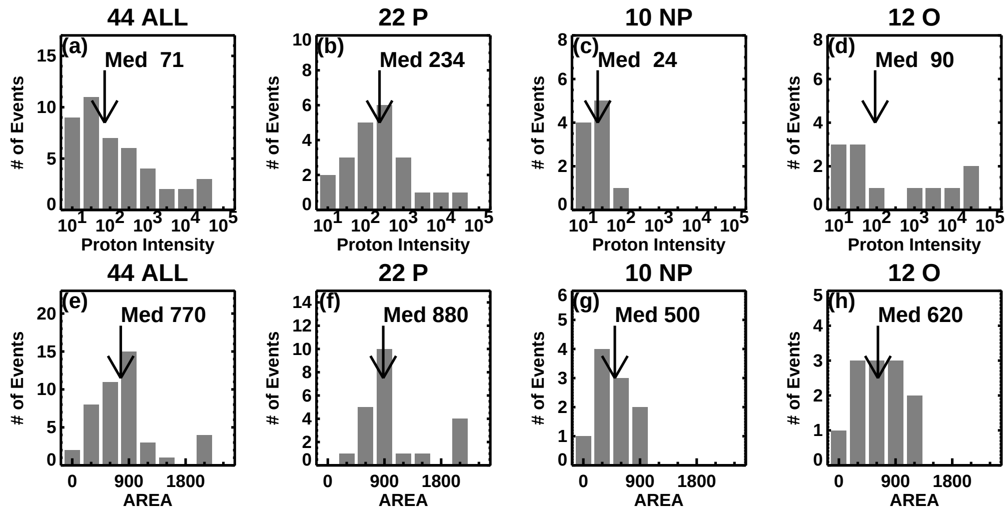

Figure 2. (a-d) Distributions of SEP intensities (pfu; 1 pfu = 1 proton $(\mathrm{cm}^2\mathrm{ssr})^{-1}$) for all the events and for the P, NP, and O events. (e-h) Distribution of active region areas (in millionths of solar hemisphere) for all events and for P, NP, and O events. The median value of the distributions is shown on the histograms.

2.2. *CME speed, Flare Size and Active Region Area*

Figure 3(b) is a scatter plot between the CME speed and the active region area. For the combined data set, the two quantities seem to be poorly correlated (r= 0.16). For the sub groups, the correlation is equally poor (r= 0.22 for P events, 0.15 for NP events and 0.01 for O events). The NP events have similar speed range as the other two, although the P events clearly occupy the higher-area side of the plot. The X-ray flare size, however, is better correlated with the active region area (r= 0.60), as can be seen in Figure 3(c). For the P and O events, the correlation is significantly smaller (r= 0.36 and 0.33, respectively). The apparent high correlation for the NP events (r= 0.74) is completely destroyed (r= 0.08) when the single outlier is dropped. Nevertheless, the flare size seems to be closely tied to the active region than the CME speed is.

3. Discussion and Conclusions

In this work, we have shown that the intensity of SEP events has no specific dependence on the area of the active region from which the associated CMEs and flares originate. The CME speed also has no significant correlation with the active region area, thus confirming the previous result that the presence of preceding CMEs makes a shock more efficient in accelerating SEPs (Gopalswamy, Yashiro, Michalek, *et al.* (2002), Gopalswamy, Yashiro, Lara, *et al.* (2003), Gopalswamy, Yashiro, Krucker, *et al.* (2004)).

We now discuss the relevance of the significant correlation that the soft X-ray flare size has with the active region area (see fig. 3c). The size of a soft X-ray flare implies intense soft X-ray emission from the flare plasma. The flare plasma is supposed to be the hot post-eruption loops containing plasma evaporated from the chromosphere (see e.g., Antonucci, Dennis, Gabriel, *et al.* (1985)). The evaporation itself is thought to be caused by electron beams precipitating into, and losing energy to, the chromosphere. Higher flare size therefore implies a higher density of heated flare plasma over a larger volume (i.e. higher emission measure). The flaring loops are generally confined to the active region, so one can understand the good correlation between flare size and active region area.

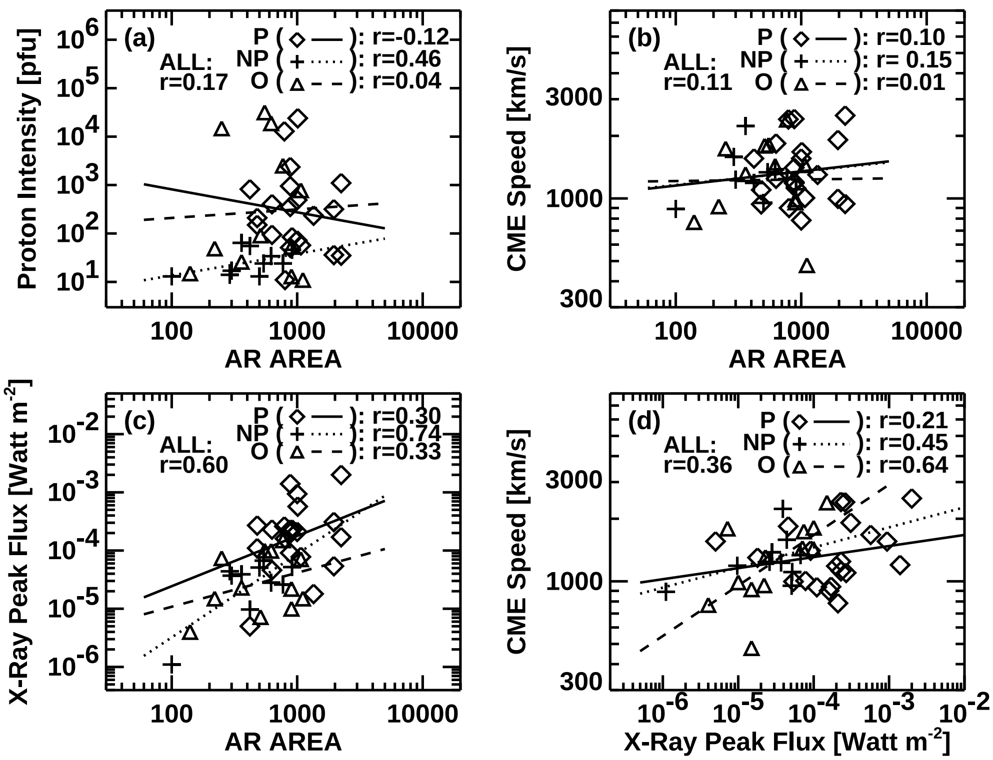

Figure 3. (a) Scatter plot between SEP intensity (pfu) and active region area (millionths of solar hemisphere). P, NP and O events are represented by diamond, triangle, and + symbols, respectively. The overall correlation coefficient, r= 0.21. The correlations coefficients for the P, NP and O events are also shown on the plots. When the single outlier NP event is excluded, the overall correlation coefficient drops to 0.15 and that for the NP events drop to 0.26. (b) Scatter plot between the CME speed and the active region area (r= 0.16). The subgroups also have similar correlation coefficients. (c) Scatter plot between X-ray flare size and active region area (r= 0.60). When the NP outlier is dropped, the overall and NP correlation coefficients drop to 0.51 and 0.08, respectively. (d) Scatter plot between the CME speed and the X-ray flare size (r= 0.42). When the NP outlier is dropped, the overall and NP correlation coefficients drop to 0.38 and 0.05, respectively.

This result may also be relevant to the previous result that the intensity of energetic (108 keV) electrons are well correlated with flare size (Gopalswamy, Yashiro, Krucker, *et al.* (2004)). If these electrons propagating away from the sun are accelerated by the same process as that of the precipitating electrons, one might expect a good correlation with the flare size.

If the SEPs are accelerated by the CME-driven shock, the SEP intensity need not have a specific relationship with the active region area. Even though the CME is rooted in the active region, the three-dimensional shock front ahead of the CME when it is within a few solar radii from the Sun is much larger than the active region area. This might explain why there is no relationship between the SEP intensity and active region area. However, a weak but significant correlation exists between CME speed and Flare size (fig. 3(d); see also Gopalswamy, Yashiro, Lara, *et al.* (2003)). This can be explained as more energetic eruptions resulting in bigger flares. It must be pointed out that the area of the active region may not be a good proxy for the free energy in an active region. The free energy is determined by the currents flowing in the corona representing the deviation from the potential field configuration. Estimates show that the free energy is of the order of the potential field energy (see e.g., Forbes (2000). One has to estimate at least the potential field energy of the active regions for a better comparison.

Acknowledgements

This research was also supported by NASA/LWS and NSF/SHINE (ATM 0204588) programs. SOHO is a project of international cooperation between ESA and NASA.

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